The U.S. geodesy crisis

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The grass-roots white paper of January 2022

America's loss of capacity and international competitiveness in geodesy, the economic and military implications, and some modes of corrective action

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Hereafter, *Bevis et al., 2022.*

Note: an interesting commentary on this white paper, called 'Is there a crisis brewing in geodesy?' has recently been published by the Australian website 'Spatial Source'.

America’s loss of capacity and international competitiveness in geodesy, the economic and military implications, and some modes of corrective action

“The U.S. is on the verge of being permanently eclipsed in geodesy and in the downstream geospatial technologies. This threatens our national security and poses major risks to an economy that is strongly tied to the geospatial revolution, on Earth and, eventually, in space.”

“Averting these dangers at such a late date will require the U.S. to invest in geodetic research and training on an *industrial* scale.”

“The situation in academia is particularly urgent because if corrective action is not taken very soon, the U.S. will no longer have the capacity to take such action at the scale required to avoid permanent disadvantage.”

“China now has more geodesists than the rest of the world combined, and its numerical advantage continues to grow. During this time period, the largest national decline (worldwide) in geodetic research and training capacity has occurred in the U.S.”

“Perhaps the most shocking example of the U.S. decline relative to China is that the number of Ph.D. geodesists in the entire DOD, including the National Geospatial-Intelligence Agency (NGA), is now approaching zero.”

The geospatial economy

The geospatial revolution began to develop explosively around the time that the Global Positioning System (GPS) achieved operational status in the early 1990s. Today, about 3.5 billion people worldwide use one or more Global Navigation Satellite Systems (GNSS), including GPS, via their smartphones, every day.

The global geospatial economy has a value of at least \$ 1 trillion per year ($\$ 10^{12}$ / yr), and perhaps significantly more. It comprises the 'Fourth Industrial Revolution'. It is arguably the most important economic and technological development since the internet, and it is still accelerating. Its military significance is comparable to its economic significance*.

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* Many satellites are built to support geodetic positioning, time transfer, geodetic imaging, geospatial monitoring, etc., and most other satellites incorporate geodetic sub-systems. Geodetic science and technology underpin most military platforms and systems, the satellite industry, aviation, shipping, logistics, many sciences (including most of the Earth sciences), many areas of engineering (e.g.driverless vehicles, drones, intelligent grids), precision agriculture, Smart Cities, computer/cell phone ecosystems, location-based services, and significant parts of Artificial Intelligence, big data analytics, and the Internet of Things.

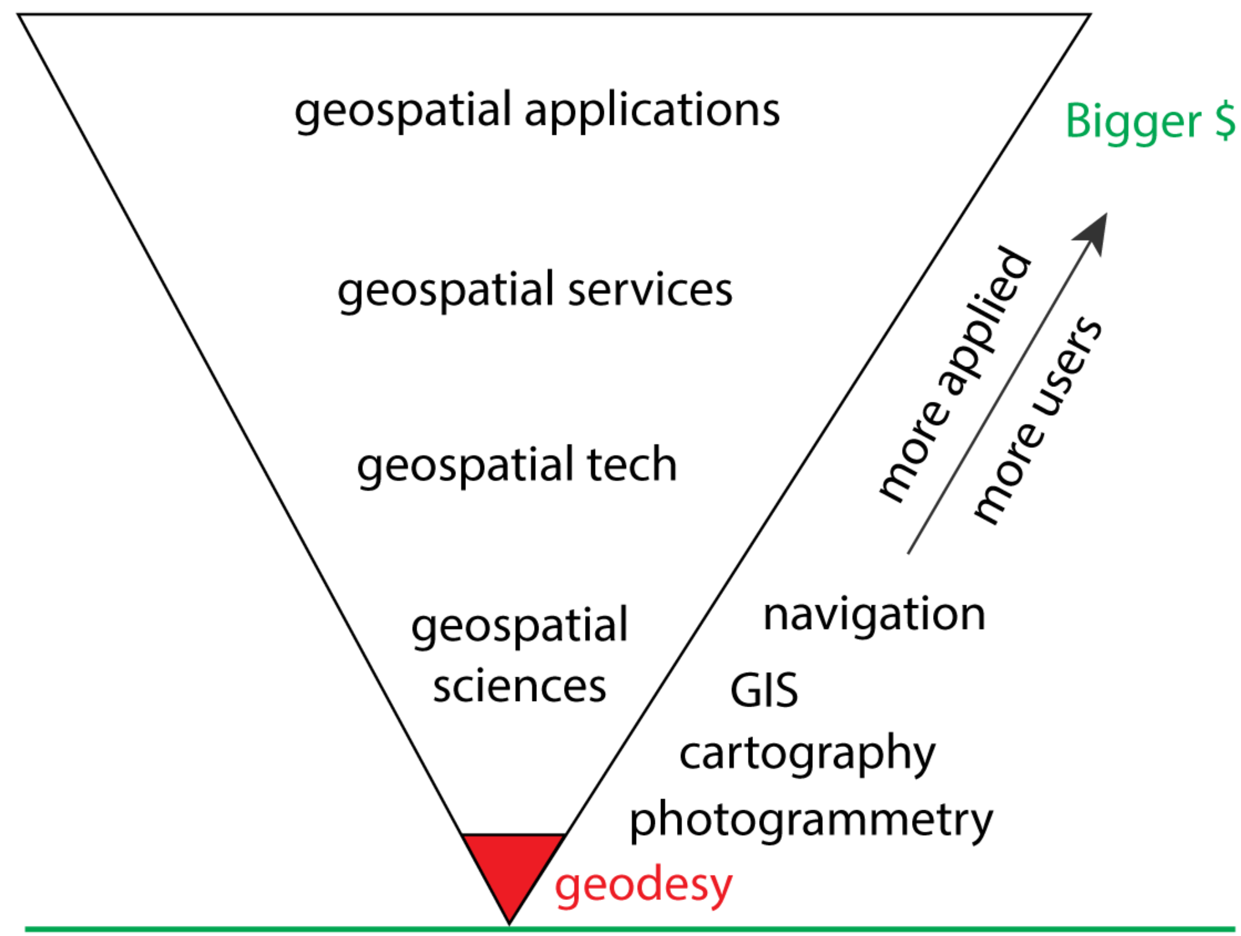
Geodesy

Geodesy is the most fundamental science of geospace*.

Geodesy provides the mathematical and physical infrastructure for the other geospatial sciences, technologies and services, and thereby underpins the entire geospatial economy.

Geodesy focuses on the representation and measurement of space, mass and time; reference systems, coordinates and orientation; gravity, rotational dynamics, and orbital mechanics; and how these quantities, processes, and systems evolve over time.

The inverted geospatial pyramid



The entire geospatial economy is supported by geodesy!

* By **geospace** we mean the solid Earth, its oceans and ice sheets, its atmosphere and ionosphere, etc., and nearby outer space.

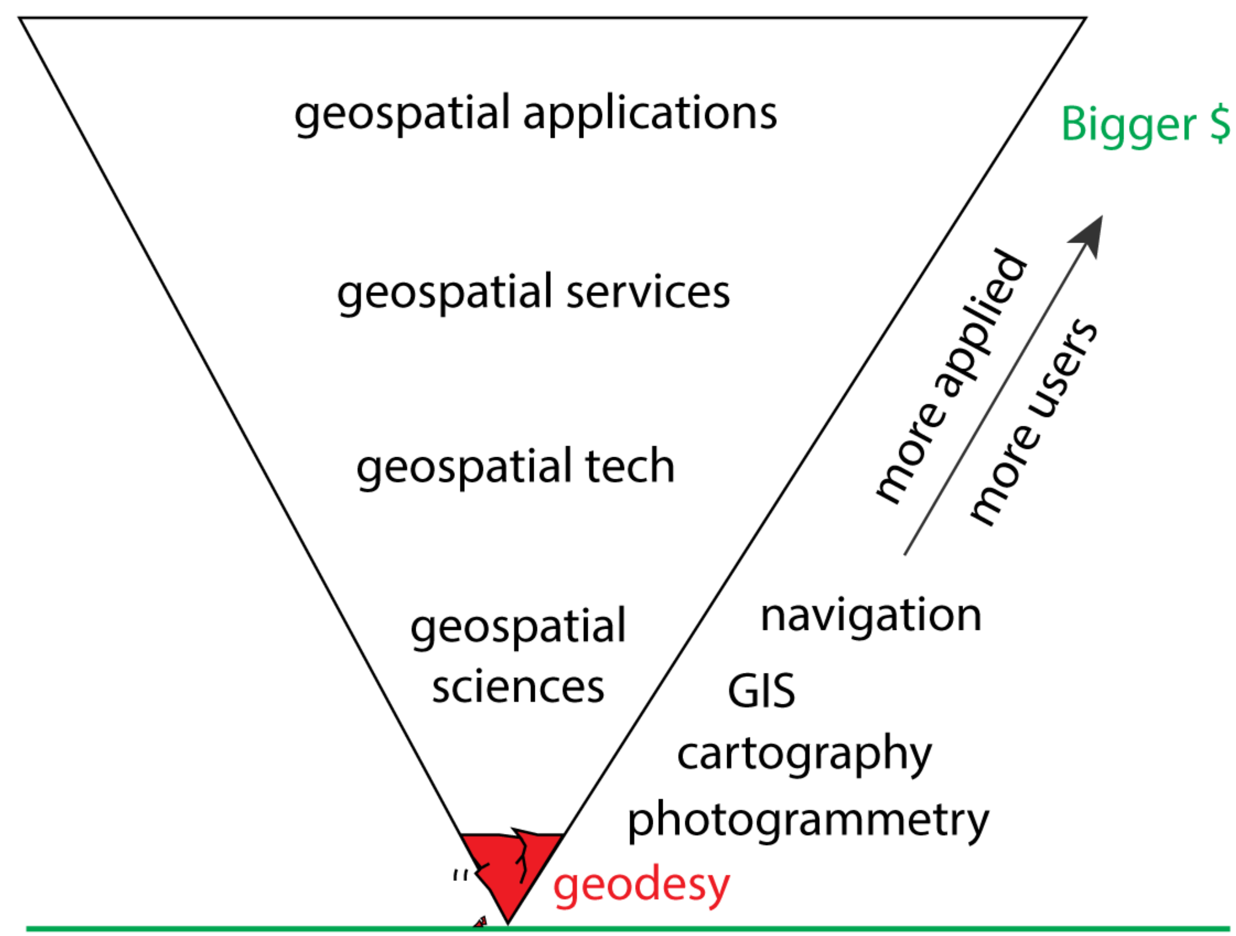
Geodesy

Given the explosive growth of the geospatial economy since the early 1990s, one might imagine that the US would have been increasing its investments in the apical discipline that supports it.

In fact, the US began to disinvest in geodesy in the early-mid 1990's, and it was Europe (especially Germany) and China that made those large and forward-thinking investments.

For decades, the U.S. government and the geospatial business community were so intent on the top half of the inverted pyramid, they were largely unaware that the scientific base of the pyramid was degrading in the USA, thereby threatening the integrity of the entire edifice.

The inverted geospatial pyramid



The entire geospatial economy was supported by geodesy!

The geodesy crisis in academia

Academic geodesy programs in the USA are now few, mostly shrinking, and scientifically balkanized*.

The NSF funds a lot of applied geodesy but almost no basic or 'pure' geodesy. Indeed the NSF community now conflates *basic* geodesy with its *applications* to geophysics and other sciences. NASA has largely internalized its funding for basic geodetic research. The USGS funds only applied geodetic research, and the NGS does not fund pure or applied geodesy (in academia) at all.

The lack of funding for basic research in geodesy *per se* has not only lowered the rate of innovation in America's geodetic technologies, it has led to very little graduate training of Americans in geodesy for two decades**. America's training capacity in geodesy is now absurdly small compared to that of Germany and China, and it continues its slow collapse.

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* In some universities there will be a GNSS geodesy group, in another an InSAR or radar altimetry group, etc. Most isolated groups won't teach geodesy *per se*, but rather their tools applications to other sciences or engineering. OSU seems to be only remaining US geodesy program that researches and teaches courses in every major branch of geodesy.

** Juliana Blackwell, the Director of NGS, wrote in 2018 "the reduction in the population of graduate students training in this field is clearly tied to declines in government funding of geodetic research in academia".

The geodesy workforce crisis

Geodesists have been warning about the national neglect of geodesy, and an impending workforce crisis, for more than a decade. We can point to 3 National Academy studies, two community reports, and a NASA report published between 2010 and 2020.

Since the mid-late 1990's, established American geodesists have been retiring more rapidly than American replacements were being trained. NGS, NGA, NASA, USGS and industry now find it very hard to hire American geodesists—because so few exist*.

The disappearance of American geodesists has also led to large numbers of young geospatial engineers who are inadequately trained in the scientific underpinnings of their own discipline**.

Tightening accuracy requirements, and a growing emphasis on real-time applications, require constant improvements in geodetic techniques and infrastructure that are increasingly being developed outside of the US.

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* Geodesy is the epicenter of the US geospatial crisis and not the other areas of geospatial science and engineering. For example, NGA has ~ 2,000 GIS specialists, and similarly large numbers of remote sensing specialists but it has ~ 2 formally trained geodesists and the rest of the DOD has none. The numbers of Ph.D. geodesists in the defense contracting and geospatial industries are also approaching zero.

**In 2019, Trevor Greening, CTO of Towill, Inc., a geospatial engineering company, stated: "we have noted that the rapid development of many new technologies has placed a premium on geodetic science knowledge" but "we see graduates insufficiently skilled to comprehend the basis of the new technology including hardware, software, and procedures".

A dawning recognition of the crisis

OSU, NGA and NGS began a lengthy study of the geodesy crisis in early 2017.

Juliana Blackwell, NGS Director, wrote in 2017
"the rapidly shrinking pool of well-trained, American geodesists now threatens our ability to achieve core aspects of the NGS mission, and we are sure this concern is shared by NGA and other agencies of the Federal Government"

In 2019, Kevin Gallagher, the Associate Director of the USGS, wrote
"The USGS shares the concerns expressed by both the NGA and the National Geodetic Survey (NGS) that the candidate pool of trained geodesists eligible to work for U.S. government agencies is currently inadequate to support our missions in the future".

In 2019, Dawn Wright, the Chief Scientist of ESRI stated
"We are well aware of the alarming shortage of geodetic scientists in the USA, and the fact that far fewer Americans have been trained in this discipline in the USA than is true in Europe, Japan and China. The American shortage has grown to its present crisis stage over a period of about two decades. China's spending on fundamental research and development, and on higher education, in geodetic science and geomatics, is probably now an order of magnitude greater than in the USA, and that gap appears to be growing".

In 2019, Neil Vancans, VP of Septentrio USA, a leading GNSS company wrote:
"It cannot be plainer that a range of serious threats will develop if we continue to allow the slow collapse of what is one of the most technologically productive of all the sciences".

Incomplete recognition of the crisis

The slowly dawning recognition of the US geodesy crisis in 2017-2019 was very welcome, but, even now (in Sept. 2022), no major corrective actions have been launched, except in the NGA.

In part this is because recognition of the crisis is incomplete. For example, the understanding in the NGS does not seem to extend to its parent agency NOAA. The understanding in the NGA's Office of Geomatics does not seem to extend to most of the DOD. The central government and its policy entities (such as OST and PCAST) still seem to be unaware of the crisis, despite the serious threats it poses to national security and our economy.

The structural relationships between US geospatial agencies may also contribute to the problem. For example, the NSF built NOTA, the most important terrestrial geodetic asset of the USA, but given its mission, NSF cannot fund it indefinitely, but wishes to hand it off to an 'operational' agency. The obvious choice is NGS, but, characteristically, NGS simply does not have the necessary resources*. Now NOTA is beginning to degrade.

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* Academic geodesists have long wondered why the NGS is located *within* the NOS. The vast geospatial end-user group almost entirely dwells on land. There are more rapidly growing and economically significant geospatial applications and businesses on land than at sea. Shouldn't NGS be positioned as a service and a funding agency like NWS and NOS? Is the lower-tier status of NGS an artifact of it being called the US <u>Coast</u> and Geodetic Survey in 1878? Even NOAA's name suggests that its *primary* interests are in the oceans and the atmosphere.

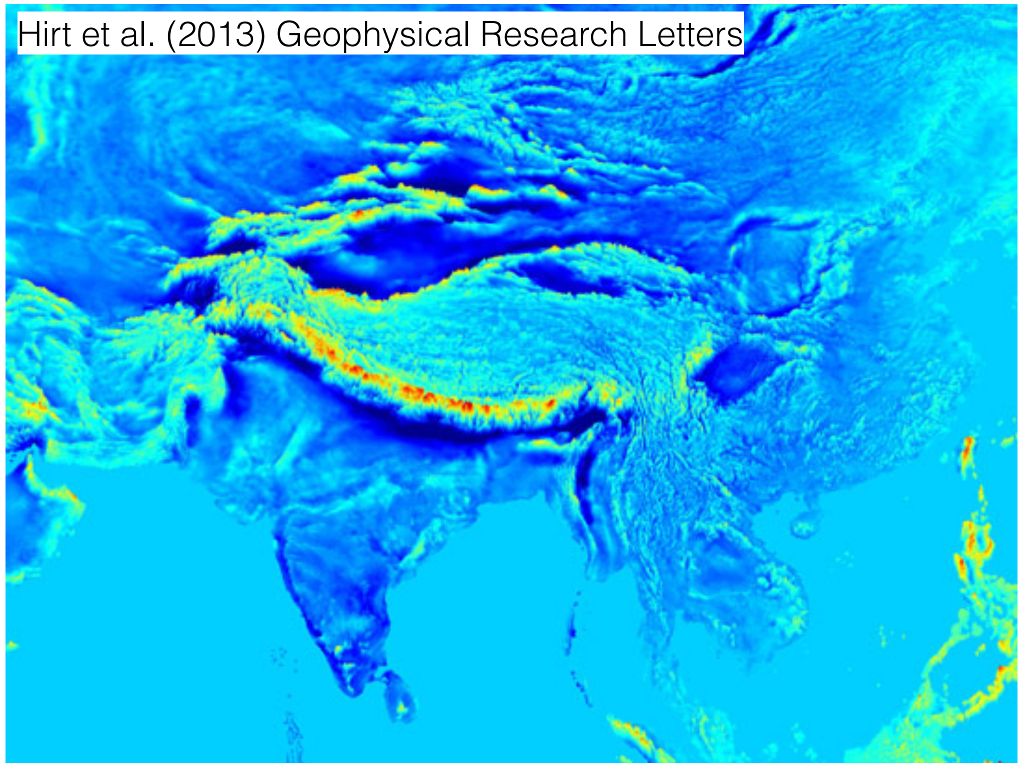
NGS's status as a non-funding-agency, means its cannot outsource R&D functions to academic geodesists, which would a benefit NGS, academic geodesy and the US geodetic workforce crisis.

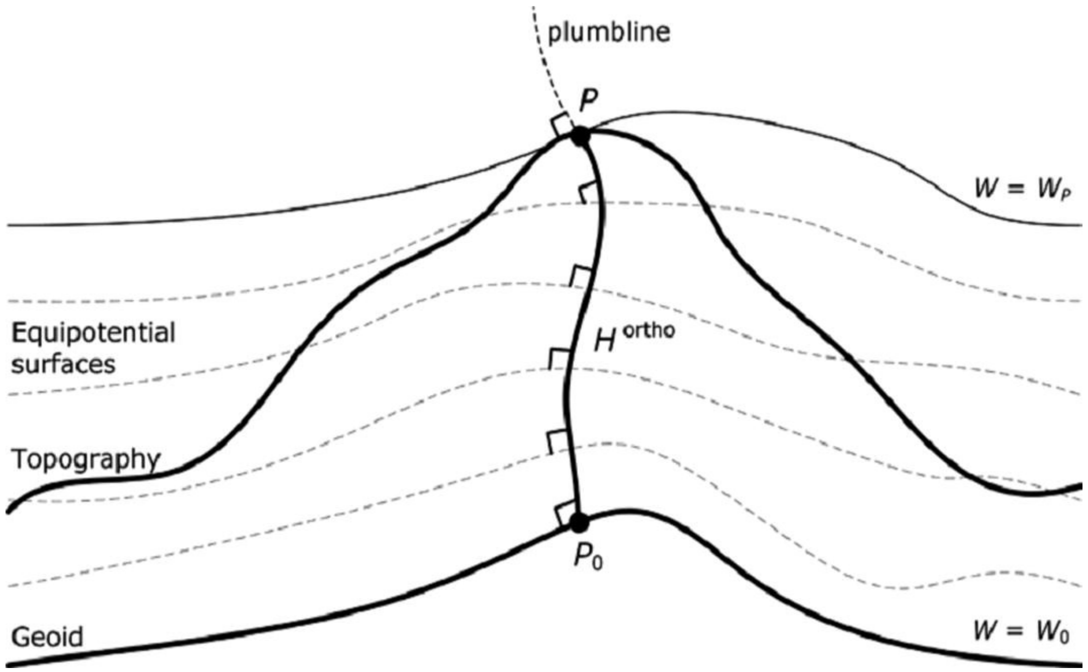
Geodesy’s continued importance

We need better models of the gravity field (geopotential, acceleration and DOV)

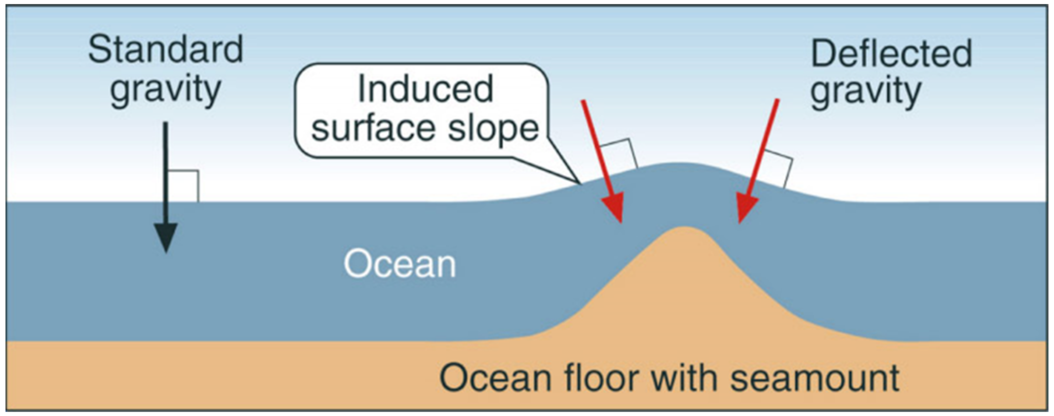
National and global gravity models are of great practical importance:

- they play a key role in vertical datums and in converting between geometrical (ellipsoidal) and orthometric (physical) heights.
- they provide gravity compensation for Inertial Navigation Systems (INS).
- in the near future, greatly improved knowledge of the geopotential field will become crucial in establishing more accurate timing systems.





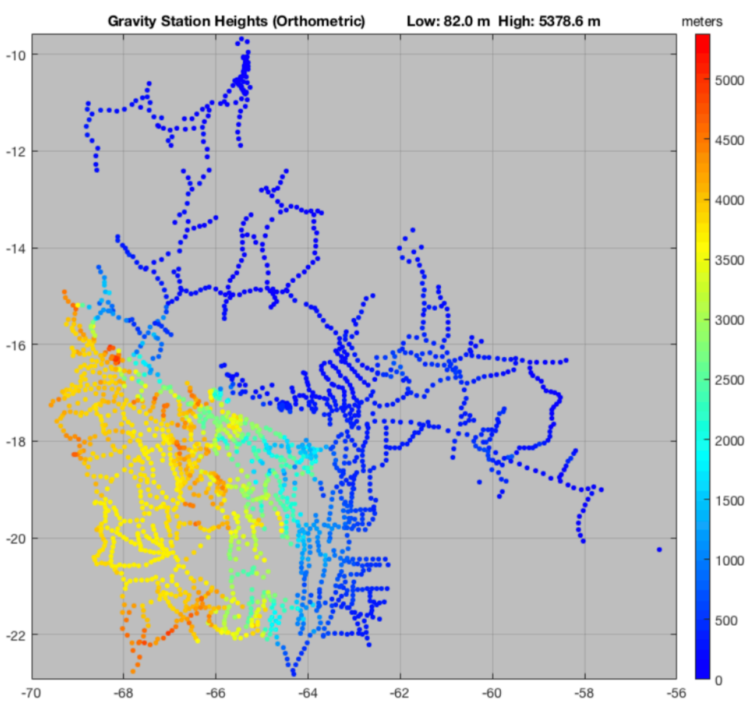
Deflection of the vertical (DOV) and curvature of the plumb line are ubiquitous. DOV variations are especially vigorous in mountainous regions.

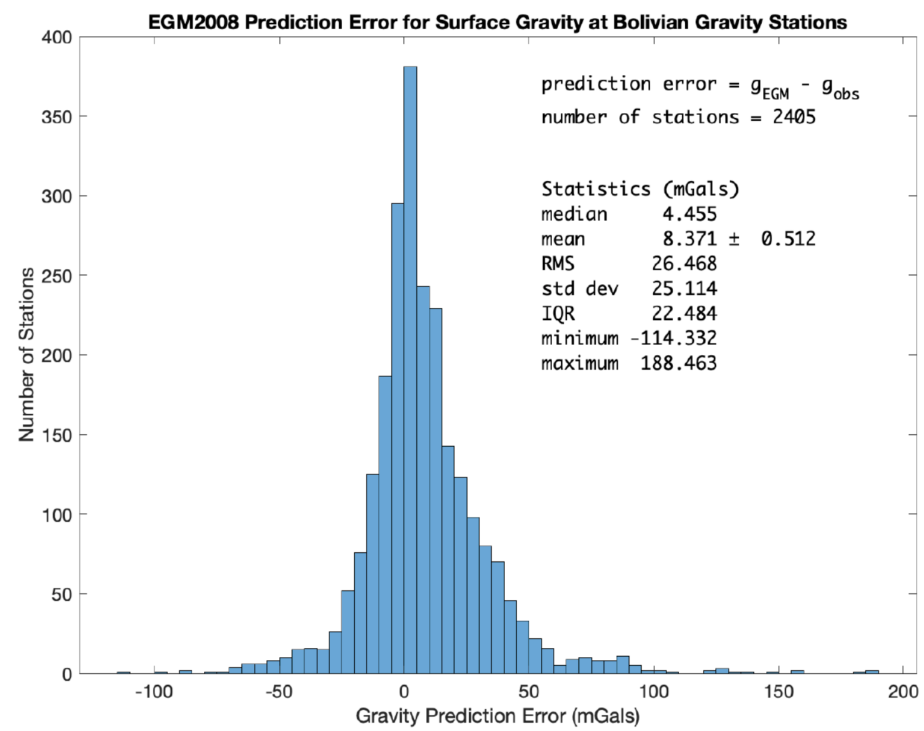


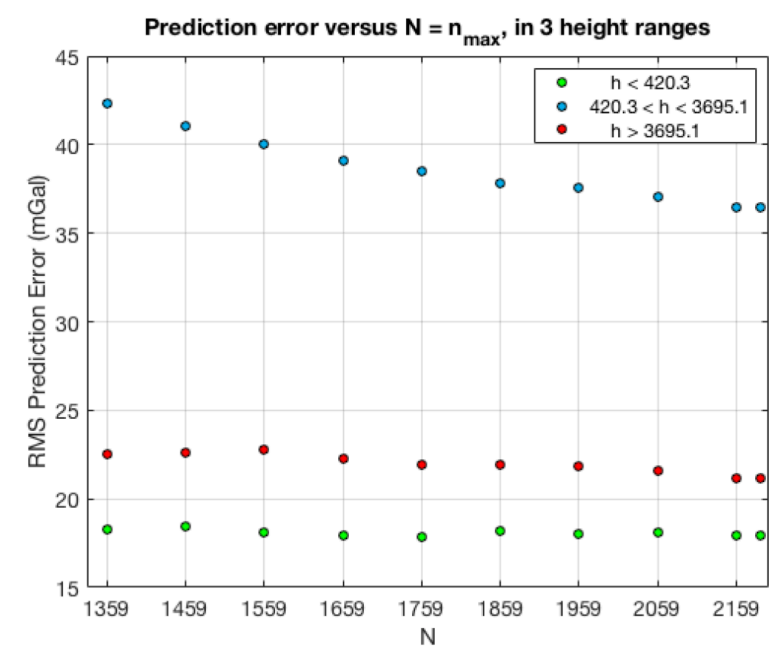
Geodesy's continued importance

We need better models of the gravity field (geopotential, acceleration and DOV)

Gravity has been measured in Bolivia at 2,400 stations, at elevations of 82 - 5,379 m. The typical uncertainty is just 0.1-0.15 mGals. This allows us to determine the level of bias and random error in the predictions of EGM2008, in an area in which most of the 'observations' used to compute the spherical harmonic coefficients were simulated using residual terrain modeling (RTM).







$N2190 \rightarrow 1359$, res $9 \rightarrow 15$ km

This level of error implies that gravity compensation errors in this region are capable of inducing INS errors of order 100 - 300 m in a low altitude flight that lasts ~40 minutes. This does not include the impact of instrumental errors in the accelerometers or the gyros. Such navigational errors will not be adequate in an era of GNSS denial.

If we can improve EGM, we can improve gravity compensation, and improve INS.

Geodesy's continued importance

Conventional and quantum networks of atomic clocks will soon need geopotential models an order of magnitude more accurate than present-day models such as EGM2008

Physicists have been making enormous strides in improving the performance of atomic clocks, increasing their frequency (f_0) and their stability. Modern optical clocks have systematic uncertainties ($\delta f/f_0$) and reproducibilities close to 1 $\times 10^{-18}$.

Relativity tells us that time runs more slowly at lower elevations (i.e. closer to a large mass). Two atomic clocks located in different places, with a difference in geopotential of δW, have a rate difference given by $(\delta f/f_0)_{grav} = - \delta W/c^2$, where c is the speed of light. Near the surface of the Earth, gravitational red shift amounts to a fractional frequency shift of 1.1×10^{-18} per centimeter of vertical displacement.

Such a sensitivity to gravitational time dilation means that optical clocks now have the ability to measure differences in gravitational potential (chronometric geodesy).

But gravitational time dilation is not so much a change in the clock rate, but a shift in the rate of time itself. If a user without an atomic clock wishes to establish a local time standard by participating in a conventional or quantum network of atomic clocks, it will be necessary to account for the gravitational potential, W, at the user's location, with an accuracy comparable to the change in W that would occur with a vertical movement of ~ 1 cm (assuming $\delta f/f_0 \sim 10^{-18}$).

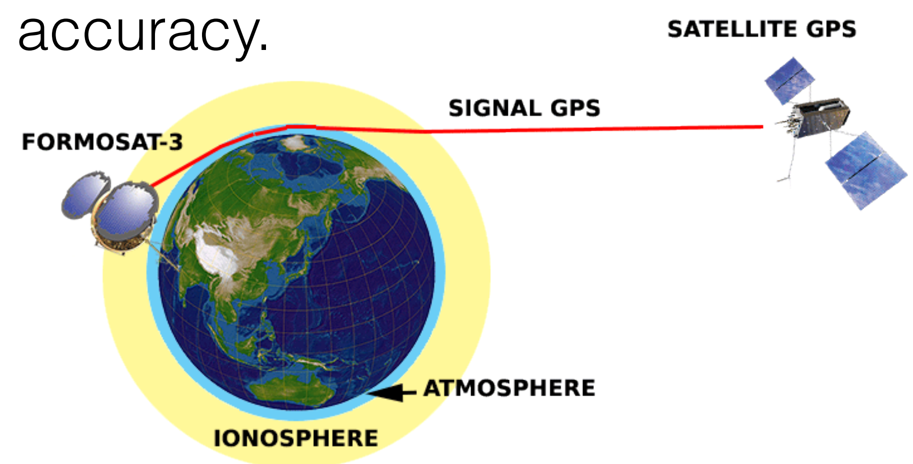
Gravitational model prediction errors are at least an order of magnitude worse than this over much of the world, particularly in mountainous areas, and in areas in which the model was constructed using RTM rather than with actual gravity observations.

Geodesy’s continued importance

Next generation satellite positioning using one or more mega-constellations of LEO satellites as well as modified GNSS constellations

Consider a large LEO constellation (cf. Starlink), with very sophisticated communications, whose satellites can receive GNSS signals and also range to each other using radio links and/or pointed laser beams. Since the LEO satellites lie above the atmosphere it should be possible to position them to ~ 1 mm in real-time.

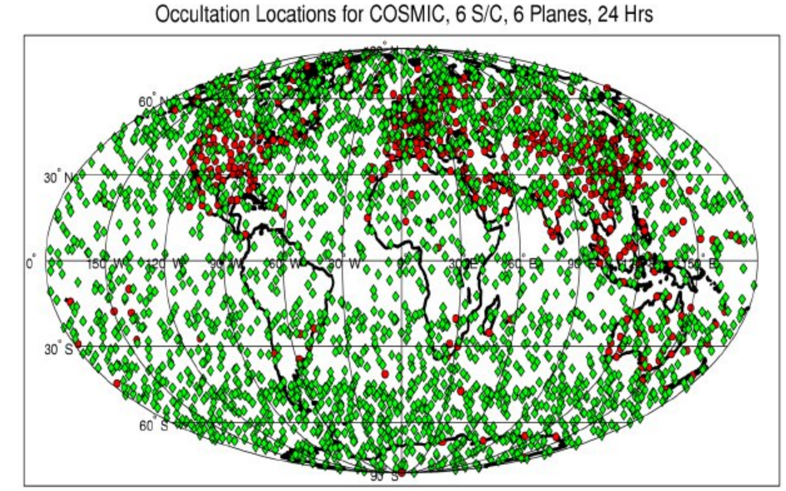
If the system can also use ground-based GPS met techniques, and the millions of occultations per day for limb sounding (cf. COSMIC), it should be possible to image almost the entire atmosphere with a temporal resolution of 15 - 30 minutes, and use a state space representation of atmospheric refractivity structure to position ground-based users against the LEO constellation with only a minor loss of real-time positioning accuracy.



This agenda would receive additional support over our land masses if the LEO satellites could also receive DORIS-like signals from ground-based telecomm towers (there are ~ 4 million, now).

Because space-time variability of the neutral delay is dominated by water vapor, and lack of knowledge of water vapor distribution is the single biggest cause of weather model prediction error, such a positioning system would revolutionize operational meteorology, and have a major impact on climate studies too.

Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs



Geodesy’s continued importance

Next generation satellite positioning using one or more mega-constellations of LEO satellites as well as modified GNSS constellations

Consider the advantages of this class of satellite positioning:

Since the LEO constellation would have high-speed, internet-like communication capabilities

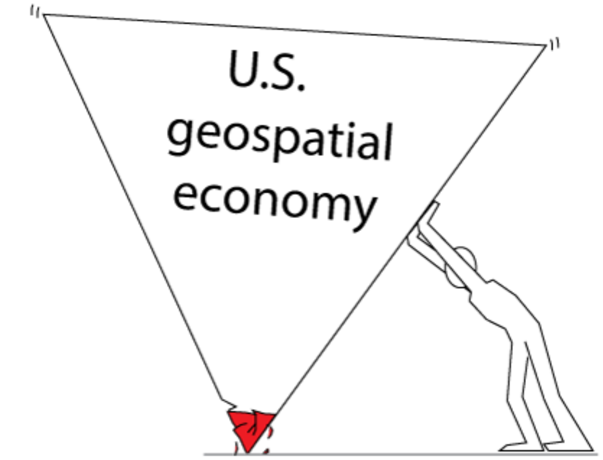
- its navigational users could communicate their ultra-accurate positions in real-time
- the system could support a wide range of encryption strategies, and implement a wide variety of access controls
- because the LEO satellite signals would be far stronger at ground-level than GNSS signals, they would be harder to jam or spoof

If the LEO satellites were equipped with downwards pointing antennas, they could acquire and communicate reflected signals, allowing the system to probe terrestrial surface state (e.g. soil humidity, or ice surface melt), sea state, etc.

By virtue of its real-time accuracy and its two-way communication architecture the system could improve the performance of existing geospatial systems (e.g. improve airborne LIDAR or gravity surveys by improving the positioning of the aircraft or drone), allow buoys to better sense tsunamis, or geodetic stations on land to improve warnings of volcanic deformation or earthquake early warning. Collision avoidance systems could be turbo-charged as well.

Such a system would probably support hundreds of new scientific, engineering, military and commercial applications that we are presently incapable of imagining. Its value would be assessed in trillions of dollars.

Reversing the U.S. geodesy crisis



The 2022 white paper suggested that the U.S. government should

(1) understand the mechanisms that have promoted a sustained unawareness of the U.S. geodetic crisis, determine which are still operating, and counter them

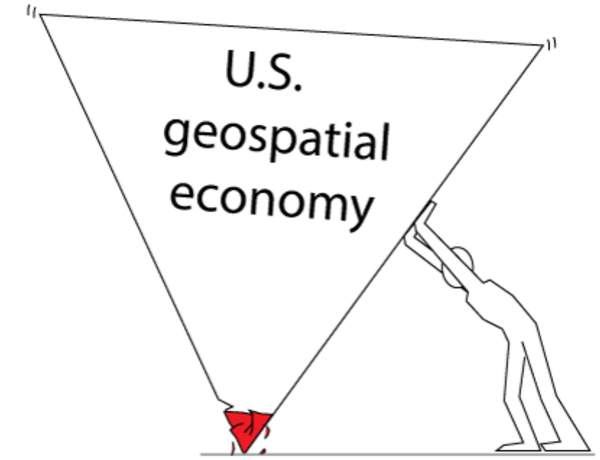
(2) take corrective actions, including major increases in funding for basic geodetic research and three distinct modes of training, and increase the number of agencies involved in that funding to make it more robust and comprehensive, and to build more geodetic partnerships

It is useful to distinguish between short-term actions, essentially *triage* (to stop the patient bleeding out before the hospital is reached) and larger scale and longer term responses (to fully restore the patient's health and vitality)

Short term actions should address problems that are both urgent and important, which, if unaddressed, will make recovery almost impossible. Obvious examples are (1) to reverse the decline in academic research and training in geodesy, and (2) to prevent further decline in important geodetic infrastructure (e.g. NOTA, VLBI/VLBA, etc).

Longer term actions should be bolder, and seek to return the US to global leadership in geodesy, geodetic technology and the geospatial economy. These actions will be far more expensive, and require considerable political support.

Reversing the U.S. geodesy crisis



Corrective actions include the following

(1) Greatly increase R&D funding in basic as well as applied geodesy.

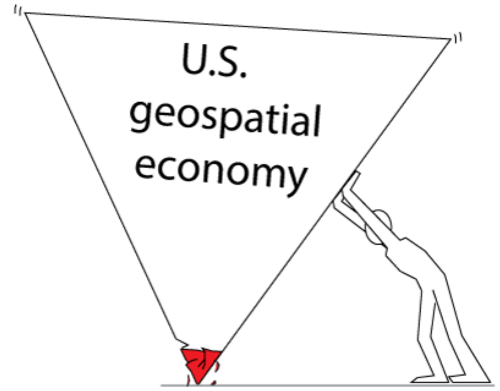
- Since different USGov agencies (NGS, NGA, NASA, USGS, Dept. Agriculture) exploit or emphasize different aspects of geodesy, it would be advantageous if all of them were engaged in the funding of basic and/or applied geodetic research.
- NSF needs to start thinking of geodesy as a science, and not just as infrastructure for other sciences.
- We should probably follow China's lead in ensuring that multiple research groups are funded to perform parallel R&D in all mission-critical areas

(2) Greatly expand training in geodesy. There should be at least three modes of training

- Mode 1 - no barrier to entry education for outreach and recruitment purposes (mostly pitched at high school and/or undergraduate levels)
- Mode 2 - in-house training of existing employees of geospatial agencies and organizations, mostly at the Masters level
- Mode 3 - training of researchers at the Ph.D. level in geodetic research groups engaged in frontier research (c.f. the Manhattan project). These Ph.D. students will eventually create the future of their own discipline.

Note that, in practice, increasing funding to academia for geodesy R&D automatically provides funds for full-time Ph.D. students embedded in geodesy research groups.

Other Asks from the white paper



(1) Organize a government review of the geodesy crisis through OST or PCAST (with support from the NAS?) But **don't** delay all actions until these reviews are completed!

(2) Prevent an imminent loss of US academia's capability to train a lot of new geodesists.

Even if every experienced academic geodesy group in the USA is training as many Ph.D. geodesy students as possible, we would still be <u>far</u> behind the present-day training capacity of China, for instance. But at least at least the US would have a chance of recovering its competitiveness.

(3) Stop the slow decline of the NGS by making it a line service like the NOS and the NWS. The NGS should become a geodesy funding agency, and it should take over and broaden the functionality of NOTA. External research partnerships with academia will help it the overcome its shortage of geodesists.

(4) Both the Office of Geomatics and the Research Directorate of NGA should greatly increase their internal and external funding of geodesy. External research partnerships will help NGA overcome its shortage of geodesists.

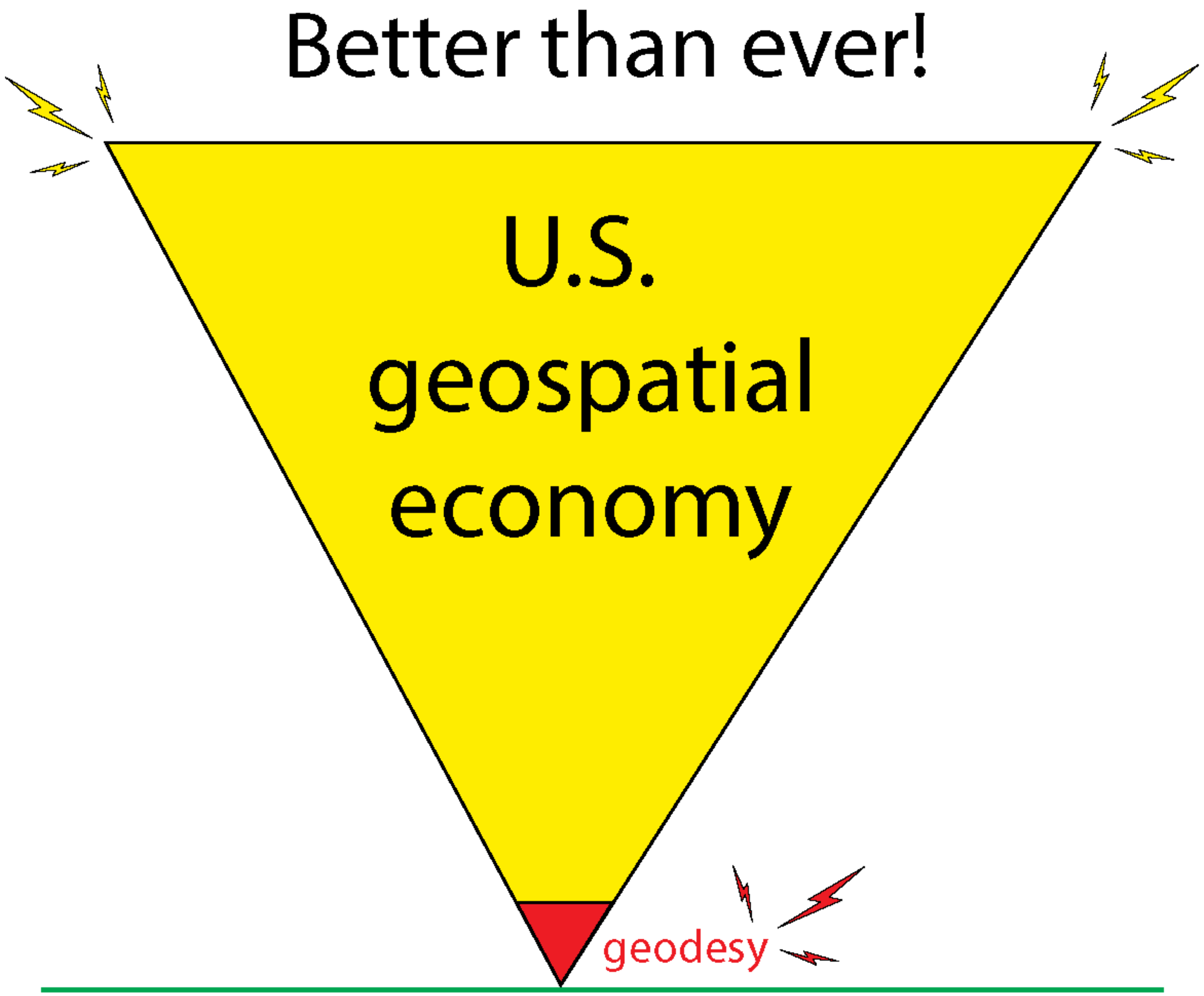
(5) The military research offices, e.g. AFOSR, ONR, USNO, and DARPA should start to fund geodesy research.

(6) NSF should develop a funding program in geodesy per se. (So far it funds applied geodesy in the service of the Earth sciences).

(7) The USGS should start to fund geodesy in areas of interest to it (e.g. earthquake early warning), and the Dept. of Agriculture and other geospatial agencies might do the same.

(8) Do everything fast - we are running out of time for any realistic recovery scenario

The potential fruits of collective action



Thanks!

Some early responses to the 2022 white paper

From a senior GNSS geodesist in NASA

It is not just BeiDou that has caught up with GPS, Galileo has clearly surpassed it. This is because technical planning and policy for Galileo is dominated by Europe's geodesists, which is not the case with GPS. The demotion of geodesy in the US has led to the 'GLONASSization' of GPS. This does not bode well for America's market share in the geospatial economy.

From a geodesist in NGS

The United Nations has established two global centers of excellence in geodesy and geomatics, one in Germany and one in China. In part this is because the US did not press for a similar role. But additionally, much of the world now believes what the white paper has emphasized, that the US has largely ceded leadership in geodetic science and technology to Germany and China, and this is just one of the consequences.

A question from an academic who specializes in geomatics

Could the geodesy crisis be resolved by NGA?

Our response:

NGA could play a major role in revitalizing American geodesy. But the problem is too large, and too pervasive for any one agency, acting alone, to reverse.